A Physophysical Experiment of the Perception of Slip Distance

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ABSTRACT

In this paper we present a slip display aimed at rendering sensations associated with a wet or lubricated surface rather than the typical dry surface presented by most haptic slip displays. The device features a perforated rotating belt to generate slip sensations with air jet streams delivered through the perforation. The presence of an air stream at the surface interface is hypothesized to decrease the perceived surface friction, giving rise to the sensation of a wet surface. The slip display was mounted on a linear track so that movement along the track resulted in a proportional slip distance, characterized by the tracking ratio (TR), the ratio of the amount of slip distance to the amount of proprioceptive distance traveled by the hand. A psychophysical experiment was conducted to investigate the effect of varying TR in order to determine the tracking fidelity necessary for the fingertip slip display to guide optimization of the device design. The just noticeable difference (JND) of the TR was found to be 5.55 with a standard deviation of 1.37. Future work will focus on refining the psychophysical experiment and testing more textures.

1 INTRODUCTION

The typical slip display consists of a rotating element that moves under the tip of the finger. By nature, these are effective for rendering dry, hard surfaces. To date, no slip display device has focused on rendering delicate tactile sensations associated with slip over truly slippery and dynamic surface such as those covered in a film of water or oil. While a simple approach would be to lubricate a slip display from a small reservoir of liquid, such an implementation would be messy, cumbersome, and unadaptable for a range of applications.

In this work, we present a new approach and device for implementing variable-friction in a slip display via the integration of air jets. We hypothesize that the reduced-friction sensation associated with running a finger pad over a surface perforated by air jets, as with an air hockey table, can be leveraged to render more fluid like surface. To this end, we constructed a device consisting of a pressurized box featuring a driven, perforated belt across its only opening. This was the contact point for the user. By toggling the air jets on and off, we could transition between rendering a fluid-like and dry surface. In the sections that follow, we detail the design of the prototype and implement a psychophysical study to guide design of future iterations of the device.

For the sake of simplifying the process of creating an airtight seal, all of the moving parts were contained inside of the box. With this sort of design, each component in the drivetrain contributed to the inertia of the slip display and reduced the transparency of the effect. Given that a slip display must move with the hand, it is desirable to have low inertia. The high fidelity motors and encoders that we employed were both large in size and heavy, neither of which is desirable. For this reason, we became interested in whether accurate position tracking on the slip surface was necessary at all.

Decreasing the fidelity of the position tracking could have other benefits as well. The control law that causes the slip display to track with the gross movements of the hand inherently introduces some noise, and the magnitude of that noise correlates with the magnitude of the gains in the control law. If it were discovered that a user were unable to distinguish within a certain range of slip distances, the control law could be optimized to decrease noise rather than create perfect fidelity in tracking. Cheaper components might also serve in place of the more expensive, high fidelity components, which would allow performance to be maximized relative to cost.

For these reasons, we conducted a study to investigate the ability of a user to determine differences between the proprioceptive distance traveled by the index finger and the rendered slip distance. We used an adaptive staircase method to determine the just noticeable difference between proprioceptive distance traveled and distance slipped under the fingerpad.

2 BACKGROUND

The ability to display the tactile sensation of slip, the relative motion between two surfaces, has been demonstrated to improve transparency in virtual reality and teleoperated systems. Haptic slip displays are being developed for applications ranging from improving grasp for prosthesis wearers [1] to enabling manipulation of paper in a virtual environment [2]. As slip displays continue to improve in range and decreased form factor, possible opportunities for integration of slip display devices also continues to grow.

A simple but effective one dimensional slip display is a rotating drum. Several research groups have implemented this design to develop devices and conduct studies on the sensation of slip. In [3], Salada et al demonstrate the potential for a rotating drum design to create sensations comparable to sliding a fingertip along a surface. Additionally, a psychophysical experiment examining slip feedback versus proprioceptive feedback, concluding that in the sensation of slip velocity, proprioceptive feedback dominated over slip. Beyond this study, investigation of simultaneous slip and proprioceptive sensations during surface interactions has been limited. The psychophysical experiment presented in this work will
seek to broaden the understanding of the relationship between tactile and proprioceptive sensations.

The user of air jet technology in haptic rendering is not a novel idea. However, air jets have been primarily used to render stiff precepts such as a hard lump [4]. Using air jets stimulation to augment tactile displays is attractive because air jet based devices have the potential to be small in form factor, reducing down to the size of the air jet nozzle. As far as the authors are aware, the only device leveraging air jets or pressure for rendering “soft” sensations is the emotional tactile sensation device by [5]. The device uses cone speakers held in the user’s hand to modulate air pressure and elicit tender emotions by creating a live, pulsing sensation. However, the aim of this work is primarily to elicit emotions which differs from our aim of rendering a virtual tactile surface of variable friction.

The T-PaD [6] is a haptic display device generates tactile patterns by modulating the surface friction of the device. By vibrating the surface to generate an air film between the surface and the fingertip, surface friction is reduced which is leveraged to control shear forces experienced by the finger during surface interactions. The relationship between air film and perceived friction reduction at the fingertip largely inspired the work that follows.

3 Device Design and Control

3.1 Physical System

The device consists of two main bodies, a fixed base and mobile carriage. As shown by the form factor in Figure 1, the base supports the carriage and houses the electronics that control the device. It is constructed from 1/8” acrylic. The carriage is attached to the base by means of a linear bearing and is actuated by a 25mm diameter, graphite brush Maxon motor via a capstan cable system. The capstan has an 8.8 mm diameter and is wrapped with stainless steel cable. This motor contains a 500 count per revolution quadrature rotary encoder to track the position of the carriage along the track. With this arrangement, the carriage has a travel of 7.5 cm, and its position can be tracked with sub-millimeter precision. A fully assembled prototype is shown in Figure 3.

The carriage encloses the components of the slip rendering mechanism. It was designed such that the user could rest his palm on the top of the enclosure and place a finger over a small aperture to access the perforated belt (as illustrated by the schematic in Figure 2). It was constructed from 1/8” acrylic. Inside the carriage, the 5/16” drive pulley was mounted on a 16 mm brushless Maxon motor with planetary gear system. In an attempt to decrease the size of the display, position was tracked with a magnetic sensor and a magnet mounted on the motor spindle. The contact point was supported with an acrylic piece with a grid cut out to allow air flow. The belt was manufactured from perforated 3M Transpore surgical tape with the adhesive removed.

3.2 Air Pressurization

An electronic Wagan air compressor capable of 35 L/min flow rate was used to pressurize the carriage based on psychophysical air jet research done by [7]. It was connected by a 1/4” ID silicon tube and placed inside of a box to reduce its audible volume. The pump, designed originally to be run from a car lighter outlet, was powered by a 12V power supply capable of supplying 13A. The carriage was sealed with caulk with the exception of the aperture serving as the contact point. Due to the nature of diaphragm pumps, there were sensible oscillations in pressure coming out of the pump. To dampen these oscillations, the volume of the carriage was increased and more flexible tubing was selected to connect the pump to the carriage.

3.3 Electronics and Control Law

Each encoder requires two interrupt enabled pins. Because each HapKit board has only one set of external interrupt enabled pins, the position of the slip drum was tracked on a second HapKit board. That position was communicated to the master board via the I2C communication protocol. A unidirectional PD control law was implemented on the master board to cause the slip drum to track with the movements of the carriage:

$$F_{slip} = k_p(K \ast x_c - x_s) + k_d(K \ast v_c - v_s)$$  \hspace{1cm} (1)

where $F_{slip}$ is the force applied to the slip drum, $k_p$ is the proportional control constant, $k_d$ is the derivative control constant, $x_c$, $v_c$, $x_s$, and $v_s$ are the positions and velocities of the carriage and slip drum, respectively, and $K$ is the tracking ratio (outlined in Section 3.5).

Both motors were powered from the master board.

Light viscous damping was applied to the carriage in order to better render a more compelling slip sensation.

$$F_{carriage} = -b \ast v_c$$  \hspace{1cm} (2)

where $F_{carriage}$ is the force applied to the carriage motor, $b$ is the damping coefficient, and $v_c$ is the velocity of the carriage.
3.4 User Feedback on Air Slip Display

User responses to the sensation were mixed. Users all agreed that the flow of air provide a distinct change to the character of the slip sensation, but the identification of the sensation was more varied, likely due to variation in the relationship between finger size and aperture size. Some users completely occluded the hole, causing pressure buildup that lead more substantial bursts of flow around the edges of the finger which distracted from the primary sensation. Others only partially blocked the hole and felt a more uniform flow of air. This group generally described the sensation in ways that were more aligned with our intended surface, commonly describing wetness. One person described the sensation as running their finger along the bottom of a shallow pool of water. The depth he described might be attributed to the fact that the flow of air comes out from under the fingertip and then continues along the edges of the finger. These results suggest that the device could be improved by redesigning the aperture for air flow to provide a more consistent experience and attempting to somehow prevent the flow from wrapping around the finger.

3.5 Changes for the Experimental Device

The carriage was redesigned for the psychophysical experiment to enable improved measurement of the parameter of interest, the slip displacement relative to the carriage movement. To eliminate inaccuracy in position tracking caused by slip and stretch in the belt as it moved between its two pulleys, we chose to render slip using a single pulley directly mounted to the motor. Air flow was not incorporated into the study in order to decrease the number of confounding variables. The same control law was implemented, though the values of the constants were tweaked. Tracking ratio, 

$$TR = \frac{\text{carriage displacement}}{\text{slip displacement}}$$

a scaling factor for the slip distance was introduced to achieve the desired slip displacements.

4 METHODS

4.1 Subjects

A total of 9 subjects (6 male and 3 females, ages 18-23) participated in this study. Seven of the subjects are right-hand dominant. All subjects were untrained and first-time users of the slip display device.

4.2 Task

A just noticeable difference (JND) threshold experiment between slip distance and proprioceptive distance was carried out. The aim of the psychophysical experiment was to determine the tracking fidelity necessary for the fingertip slip display in order to guide optimization of the device design. We define the tracking ratio (TR) as the distance slipped under the fingertip relative to the proprioceptive distance traveled. As TR approaches unity, the necessary tracking fidelity for the device increases. In each experiment, to simulate levels of fidelity we render for the user various TR values on the slip display. Each user then interacts with the slip display and answers whether the perceived TR is equal to unity, which would relate to equal distance tracking.

4.3 Procedure

Subjects were seated a fixed distance from a table on which the slip display rested in order to maintain consistency in proprioceptive intensity. A double “1up-2down” randomly interleaved staircase procedure was implemented. Users were instructed to place their dominant hand on top of the carriage and lightly rest their index fingers on the slip drum inside the aperture. Then the user was given a learning period of up to 3 minutes to interact with the device while TR = 1 and become familiar with the sensation. For each trial, the TR for the slip display was set and the user was instructed to freely explore by moving the carriage back and forth along the linear track for up to 30sec. The user then responded with “Yes” or “No” to the question “Does the slip distance at the fingertip feel distinct from the distance traveled by the finger through space?”

The user’s response determined the TR for the next trial. In a “1up-2down” staircase procedure, two successive ‘yes’ responses on one staircase decreased the TR stimulus by one step. TR was increased a step after a single ‘no’ response. Randomly interleaving a descending and ascending staircase series reduced the effect of bias and sequential dependency. The experiment terminated when the user had indicated 4 transitions for each staircase. For the ascending staircase TR began at 1.0 while the descending began at 8.0. The step for each staircase in either direction was 0.5 until the first reversal in the staircase. The step size in subsequent trials was reduced to 0.25. A transition along a staircase is defined as the point where the TR switches between increasing to decreasing or vice versa.

4.4 Data Analysis

We analyzed both the ascending and descending staircase for each subject in order to determine if the direction of approach influences the JND of the tracking ratio. We assumed a null hypothesis that the ascending and descending staircase groups across all subjects have the same average (i.e. that the two groups are really just two independent samples from the same population).

We averaged the last three reversals of each staircase in order to find the average JND for each trial. We then compared the ascending to the descending staircase averages using a two-way ANOVA test in MATLAB in order to test the null hypothesis.

We considered two independent variables: staircase type (ascending or descending) and subject. We assumed a model of

$$TR_{R_{i,j}=x}=b_0 + b_1 + b_2j$$

where $TR_{R_{i,j}=x}$ is a matrix of tracking ratios organized first by staircase type (i) and then by subject number (j), $b_0$ is the error matrix, $b_1$ is the matrix of staircase types (alternating 1 and 2 for descending and ascending, respectively), and $b_2$ is the matrix of subject numbers. If the null hypothesis was not rejected, we proceeded to average all subject JNDs together to find a resultant mean JND and standard deviation.

5 RESULTS

Figure 4 shows plots of both staircases for a representative subject (Subject 1), and Table 1 shows the pertinent results for all subjects. Reported as mean +- standard deviation, the average ascending JND tracking ratio across all subjects was 5.31 +- 1.91, and the average descending JND tracking ratio was 5.79 +- 1.35. The two-way ANOVA test failed to reject the null hypothesis for both independent parameters (p=0.470 for staircase type and p=0.149 for subject number), meaning that we can safely assume that the two averages are not significantly different from each other. We therefore averaged all tracking ratios across all subjects together in order to yield an overall average of 5.55 +- 1.37.

6 DISCUSSION

An average TR of 5.55 shows a promising future for the development of commercial tactile slip displays. Subjects could not distinguish the difference between proprioceptive movement and relative tactile slip until the drum was slipping approximately five and one-half times the amount of track movement, meaning that high-fidelity position tracking is not at all necessary to render compelling slip sensations. Commercial slip displays could implement cheaper motors and less exacting control laws while suffering no losses in perception.

One feature of the data is that they are extremely variable (the standard deviation is 25% of the average). We believe this occurred...
slip sensations across a variety of conditions. Would round out the information necessary to convey compelling higher than 1 as opposed to lower, knowing the lower threshold per subject. Though we think it is easier to implement stable TRs JND below K=1, which would have required two more staircases TR JND, but given more time, we wished to also test for the TR. Finally, Our current study searched for the upper threshold on the so rough as to stall the motor if too much normal force was applied.

because of the novelty of the sensation – not many people have felt a simulated slip sensation before, and so most were unsure of what exact kind of sensation they were looking for. A second study with the same users may be merited to evaluate the effects of learning on the JND.

Many subjects asked during the experiment why we did not present the reference (K=1) on every trial. This experiment focused not on comparing against TR=1 but on comparing against the proprioceptive movement of the hand and arm. A future study could focus on JND of variable TR to TR=1.

Our study could be improved in a number of areas, but the major limiting factor was time. Given the short timeframe of the class, we had to simplify our study beyond our original goals. We first wished to use a larger number of reversals to hone in on a more accurate JND. We think eight-to-ten reversals (with averaging the last four reversals) would have been sufficient to obtain better information. Second, it may be that perception of slip changes drastically with texture, so we wished to test a variety of textures – the smooth surface of the drum itself, a few different kinds of medical tape, and with texture, so we wished to test a variety of textures (including the slippery sensation generated by the air jet).

For future studies, we wish to determine the lower JND threshold (the TR below 1), use a larger number of reversals in our adaptive staircase method, and test over a variety of textures (including the slippery sensation).

7 Conclusion
We developed a 1-degree-of-freedom tactile slip display that uses an air jet passing through a perforated belt to render slippery surfaces under the fingertip as the user moves the device along a linear track. The device combines the proprioceptive sensation of full-arm movement with a virtual slip sensation opposing the direction of movement.

We conducted a user study using a textured surface (without air) to determine how different amounts of slip relative to the motion of the track is perceived by human subjects. To do so, we defined the tracking ratio (TR) as the distance the slip drum moves relative to the distance the hand has moved along the linear track, where a TR of 1 means the drum tracks the position of the hand exactly. Using both an ascending and descending adaptive staircase method, we determined that the user cannot notice the difference between proprioceptive and slip movement for TRs up to 5.55, meaning that the drum can move up to 5.55 times as much as the hand before the user notices an unnatural slip sensation. Such a wide bandwidth could allow for commercial slip displays to use less expensive motors and looser position tracking while still rendering a compelling slip sensation.

For future studies, we wish to determine the lower JND threshold (the TR below 1), use a larger number of reversals in our adaptive staircase method, and test over a variety of textures (including the slippery sensation)

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